Supersymmetric Dark Matter 2004[*]

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ABSTRACT

Recent cosmological data allow to determine the universal Dark Matter (DM) density to a precision of about 10%, *if* a simple, well–motivated ansatz for the spectrum of primordial density perturbations is correct. Not surprisingly, a thermal neutralino $\tilde{\chi}_1^0$ will have the correct relic density only in "small" regions of parameter space. In particular, for fixed values of the other parameters, the allowed region in the $(m_0, m_{1/2}$ plane (in mSUGRA or similar models) seems quite small, if standard assumptions about the Universe at temperature $T \simeq m_{\tilde{\chi}_1^0}/10$ are correct. I argue that the allowed parameter space is actually still quite large, when all uncertainties are properly taken into account. In particular, the current lower limits on sparticle and Higgs masses that can be derived within mSUGRA do *not* change appreciably when the DM relic density constraint is imposed. I also show that deviating from mSUGRA does not alleviate the fine-tuning required to obtain the correct relic density, unless one also postulates a non–standard cosmology. Finally, I briefly discuss claimed positive evidence for particle Dark Matter.

1. Introduction

We live in an era of precision cosmology: the statistical errors of several cosmological measurements have now reached the percent level. A prime example is the celebrated "WMAP" data (which include data from smaller experiments as well) on the cosmic microwave background (CMB). Using these data in combination with other observations of the large–scale structure of the Universe, *and* making reasonable assumptions about the early Universe, one can extract several quantities that are of interest to (astro)particle physicists [1]. These include in particular the scaled non–baryonic Dark Matter (DM) density $\Omega_{\rm DM}$ multiplied with the scaled Hubble constant h:

$$\Omega_{\rm DM} h^2 = 0.113 \pm 0.009 \, . \tag{1}$$

As emphasized above, one has to make assumptions about the early Universe in order to derive Eq.(1). In particular, one has to assume a functional form for the "power spectrum" (essentially, the Fourier spectrum) of primordial density fluctuations which seed structure formation. The result (1) is valid for a nearly scale–invariant power spectrum, with slowly varying spectral index [1]. This ansatz is well motivated from inflation [2]. Moreover, a slightly different ansatz (a simple power law) gives very similar results. However, recall that the CMB spectrum essentially measures a function of one variable, usually taken to be the angular mode variable ℓ. If the primordial power spectrum, another function of one variable, is left unconstrained, a measurement of the CMB anisotropies could

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[*]Plenary talk at *SUSY04*, Tsukuba, Japan, June 2004

not determine *any* parameters other than the initial power spectrum, which is of little immediate interest to particle physicists.

Of course, the fact that a simple, well–motivated ansatz for the primordial density fluctuations leads to a reasonable description of the CMB (and related) data for some values of the relevant cosmological parameters (including $\Omega_{\rm DM}$) is highly nontrivial. However, the description of these data, including Eq.(1), also has a couple of puzzling features. In particular, on very large angular scales the anisotropies are somewhat smaller than expected. This $\sim 2\sigma$ discrepancy has triggered numerous speculations, ranging from the quite prosaic (e.g. models with more than one inflaton field [3]) to the fairly exotic (e.g. models where the Universe has nontrivial topology [4]).

Secondly, the same fit that produces Eq.(1) also requires that the Universe should have been re–ionized at redshift $z = 17 \pm 5$ [1]. The time when nuclei and electrons first combined to firm a neutral gas defines the famous surface of last scattering of the CMB photons (at $z \sim 10^3$), since a neutral gas is essentially transparent while an ionized plasma is not. In today's Universe most gas is again not ionized. The standard explanation for ionization is that the earliest generation of stars, called "population III" by astronomers[†], emitted enough UV radiation to re–ionize the Universe. However, in the quite recent past the existence of stars (in galaxies) at redshift $z \geq 5$ was thought to be quite challenging for standard CDM cosmology; now a significant density of stars at redshift $z \simeq 17$ seems required. This has led to speculations [5] that the early re–ionization might have been due to the (radiative) decay of some long–lived massive particles. Note that these particles would have contributed to $\Omega_{\rm DM}$ at the time of last scattering of CMB photons, but would have decayed by now.

The upshot of this lengthy discussion is that Eq.(1) should be taken with a grain of salt. Note that the error given there is purely statistical. It should be clear that this measurement also has a systematic uncertainty, but I do not know how to estimate it. For the remainder of this write–up I will assume that $\Omega_{\rm DM}$ falls in the 99% c.l. confidence range

$$0.087 \leq \Omega_{\rm DM}h^2 \leq 0.138. \tag{2}$$

A particle χ has to satisfy several fairly obvious conditions in order to qualify as a DM candidate: it must be very long–lived, $\tau_\chi > 10^{10}$ yrs; it must be electrically and (most likely) color neutral, since otherwise it would bind to nuclei, forming exotic isotopes in conflict with experimental limits [6]; its scattering cross section on nucleons must be below the experimental limits from direct WIMP searches [7]; and its relic density must fall in the range (2). If we want χ to be a sparticle in the visible sector of the MSSM, the first three requirements uniquely single out the lightest neutralino, $\chi = \tilde{\chi}_1^0$; a sneutrino would violate the direct WIMP search limits [7] by several orders of magnitude [8]. However, χ could also reside in the "hidden sector" thought to be responsible for the spontaneous breaking of supersymmetry. In the following section I will discuss the simplest scenario,

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[†]Astronomers count backwards. The most recent generation of stars, including our Sun, is called population I. Old population II stars can be found e.g. in globular clusters. No population III stars have been identified, but they have to exist (or at lest, to have existed), since the initial chemical composition of population II stars differs significantly from that of the primordial post–BBN Universe.

thermal $\tilde{\chi}_1^0$ DM in constrained models assuming standard cosmology, while sec. 3 deals with other possibilities. Some claimed positive observational evidence for WIMP DM will be discussed in Sec. 4, before concluding in Sec. 5.

2. The simplest scenario

The lightest neutralino $\tilde{\chi}_1^0$ owes its popularity as DM candidate to several features. Under some (rather mild) assumptions about the early Universe the $\tilde{\chi}_1^0$ relic density can be calculated as function of particle physics parameters only; this gives the desired value for some regions of parameter space even in constrained models like mSUGRA ($\equiv$ CMSSM) [9]. Similar statements also hold for other thermal WIMP candidates, but they have little [10] or no [11] independent motivation from particle physics.[‡] Moreover, the hypothesis that $\tilde{\chi}_1^0$ forms the DM in our galaxy can be tested experimentally; in fact, as of this writing there are at least two claims for a positive signal (see below).

In the post–WMAP era the neutralino DM candidate has nevertheless come to be viewed more critically. This can at least partly be explained sociologically: all simple calculations involving $\tilde{\chi}_1^0$ DM have been performed, and phenomenologists (like me) have to keep occupied. One complaint is that the size of the allowed parameter space shrinks drastically when the constraint (2) is imposed, see Fig. 1. This can be dismissed out of hand: it is not surprising, and is in fact highly desirable, that a precision measurement reduces the size of the viable parameter space. In the limit of vanishing experimental error a measurement should reduce the dimension of the parameter space by one. (For example, the measurement of M_Z is generally used to determine $|\mu|$ in mSUGRA.)

However, for the time being we are still quite far away from a situation with negligible experimental errors. In fact, both the experimental errors on input quantities (like the top mass m_t) and experimental measurements (like the constraint (2) and the magnetic moment of the muon [13]), and theoretical uncertainties of the spectrum calculation should be taken seriously when assessing the currently allowed parameter space of mSUGRA (or any other model).

This is illustrated by Fig. 2, which shows the lower bounds on a few sparticle and Higgs masses in mSUGRA for $\tan\beta = 20$. For the first set of points I have set $m_t = 178$ GeV, $A_0 = 0$, $\mu > 0$, and scanned over m_0 and $m_{1/2}$[§], discarding all points that violate any of the sparticle or Higgs production limits from LEP [6]. The spectrum has been calculated with the latest version of Suspect [14]. Note that this first set of points does not include the constraint (2), nor does it include any constraints on $Br(b \to s\gamma)$ (since this latter constraint can be evaded [15] by introducing some $\tilde{s} - \tilde{b}$ mixing, without significantly changing anything else in the spectrum). I did impose a mild version of the g_μ constraint [13], obtained by taking the envelope of the 2σ regions calculated using τ decay and $e^+ e^-$ annihilation data, respectively, when evaluating the SM prediction for g_μ. This gives

$$-5.7 \cdot 10^{-10} \leq a_\mu^{\text{SUSY}} \leq 47.1 \cdot 10^{-10} \,. \tag{3}$$

[‡]Note in particular that models with "universal" extra dimensions, which contain a DM candidate, do not even pretend to solve the hierarchy problem.
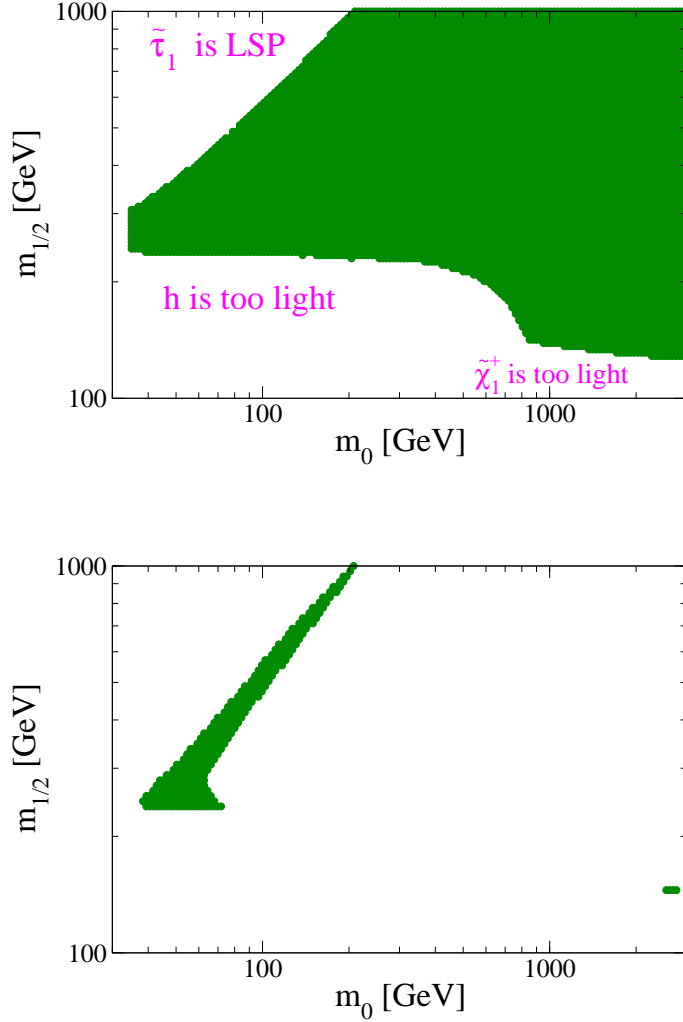
[§]I follow the notation of [12].

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Figure 1: The allowed region in the $(m_0, m_{1/2})$ plane in mSUGRA with $A_0 = 0$, $\tan\beta = 10$, $m_t = 178$ GeV and $\mu > 0$ without (top) and with (bottom) the DM constraint of Eq.(2).

We see that under these assumptions mSUGRA requires most sparticles to have masses well above the direct experimental lower bounds. Only the chargino mass saturates the LEP value of about 104.5 GeV. For example, first generation squark masses are required to lie above 630 GeV. Recall, however, that I have more or less arbitrarily fixed various parameters when determining these lower bounds. In particular, the top mass comes with an error (from the direct measurement) of 4.3 GeV, leading to a 90% c.l. allowed range

$$171 \text{ GeV} \leq m_t \leq 185 \text{ GeV}. \tag{4}$$

Allowing m_t to lie anywhere in this range significantly reduces the lower bounds. This is true in particular for the heavier neutralinos and chargino: the bound on $m_{\tilde{\chi}_3^0}$ drops from about 380 to 140 GeV; the latter is the lower bound that holds in a general MSSM with gaugino mass unification, given the constraint $m_{\tilde{\chi}_1^\pm} > 104.5$ GeV. This big jump occurs since for smaller m_t the so–called focus point of hyperbolical branch region [16] becomes
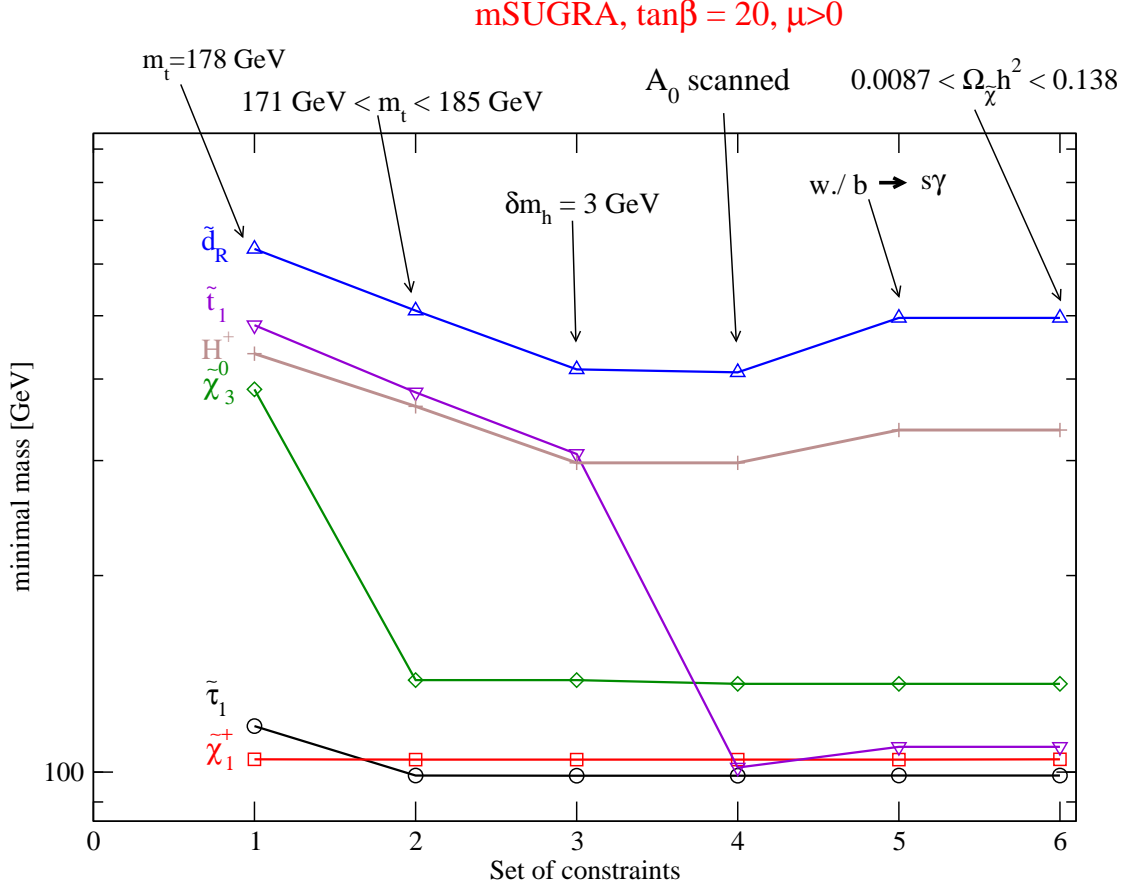
Figure 2: Lower bounds on some sparticle and Higgs boson masses predicted by mSUGRA under various assumptions; see text for details.

accessible again, which combines large m_0 with rather small μ. Note that now also the $\tilde{\tau}_1$ mass is directly given by its LEP lower bound of about 98 GeV (assuming an upper bound on the $\tilde{\tau}_1$ pair production cross section; presumably somewhat smaller $m_{\tilde{\tau}_1}$ are allowed for small $\tilde{\tau}_1 - \tilde{\chi}_1^0$ mass splitting). The lower bounds on the masses of the other scalars are also reduced, chiefly because larger m_t mean larger values of the mass of the light Higgs boson h, allowing to reduce the sparticle mass scale [17].

In the next step I have introduced a theoretical uncertainty of 3 GeV on the calculation of m_h [18]. In practice this moves the LEP Higgs limit down to about 111 GeV (unless $\tan\beta$ is very large; see below), which again reduces the lower bounds on scalar masses.

So far I have kept $A_0 = 0$ fixed. Scanning over this parameter, subject to the requirement that the weak–scale (!) scalar potential should not have deeper minima breaking color or charge.¶ This leads to a further mild reduction of the SUSY mass scale needed

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¶In other words, the so–called "UFB" constraints [19] are not imposed here. They significantly reduce the parameter space even for $A_0 = 0$, but even if a "UFB" minimum exists, our (false) vacuum is usually

to satisfy the Higgs search limits. Much more significantly, it allows large $\tilde{t}_L - \tilde{t}_R$ mixing, thereby moving the bound on $m_{\tilde{t}_1}$ down to its lower limit from LEP. (Tevatron limits do not apply, since the mass splitting with the LSP is not large enough.)

For the fifth set of bounds I have in addition imposed the constraint [20]

$$2.65 \cdot 10^{-4} \leq Br(b \to s\gamma) \leq 4.45 \cdot 10^{-4} . \tag{5}$$

For the given moderately large value of $\tan\beta$ this has some impact on the lower bounds of the heavy scalars, e.g. increasing the limit on the mass of first generation squarks by about 20% to just below 500 GeV. On the other hand, now finally also including the DM relic density constraint (2) has almost *no* impact on the lower bounds shown in Fig. 1. Table 1 shows that this is also essentially true for the absolute lower bounds one derives in mSUGRA after also scanning over $\tan\beta$. Introducing the constraint (2) increases the lower bound on the LSP mass by some 5 GeV (to a value close to $m_{h,\mathrm{min}}/2$, to benefit from enhanced $\tilde{\chi}_1^0$ annihilation through h exchange), but none of the other lower bounds moves significantly. These mSUGRA lower bounds are quite close to those one would obtain within a more general MSSM, as long as one keeps the gaugino masses unified at the GUT scale, and requires that all squared squark and slepton masses are non–negative up to that scale.

Table 1: Absolute lower bounds on some sparticle and Higgs masses (in GeV) in mSUGRA after scanning over the entire allowed parameter space, without and with the DM constraint (2); see text for further details.

Particle	W/o DM constraint	With DM constraint
$\tilde{\chi}_1^0$	50.7	55.8
$\tilde{\chi}_1^\pm$	104.5	104.5
$\tilde{\chi}_3^0$	135.1	136.5
$\tilde{\tau}_1$	98.7	98.7
h	91.0	91.0
$H^\pm$	128.4	128.4
$\tilde{g}$	371	384
$\tilde{d}_R$	411	411
$\tilde{t}_1$	102	102

I should emphasize that these bounds are saturated in quite different regions of parameter space. As noted earlier, the masses of the heavier $\tilde{\chi}$ states are minimized for $m_0 > 1$ TeV and keeping m_t close to the lower end of the range (4), while the first generation squark and slepton masses are minimal for the largest allowed m_t, small m_0 and $m_{1/2}$, and moderate $\tan\beta$ (where the g_μ and $b \to s\gamma$ constraints are not significant). Finally, the lower bounds on the Higgs masses are saturated at $\tan\beta = 60$; no solution is found for significantly larger values of this parameter.

We thus see that the additional restrictions of parameter space from the constraint (2) applied to a stable $\tilde{\chi}_1^0$ as DM in some sense are not very severe; at least they do not change

extremely long–lived.

significantly the lower bound on the mass of any new particle predicted by mSUGRA. Nevertheless it is often argued that this constraint leads to additional finetuning, since it can be satisfied only in "peculiar" regions of parameter space: the "focus point" region; the co–annihilation region, with small mass splitting between the LSP and either the $\tilde{\tau}_1$ [21] or $\tilde{t}_1$ [22]; or the "Higgs pole" or "funnel" region, where $2m_{\tilde{\chi}_1^0} \simeq m_A$ [23]. The first two of these regions are very close to the edge of theoretically forbidden regions (by the requirement of consistent electroweak symmetry breaking and of a neutral LSP, respectively). Moreover, in all these cases $\Omega_{\rm DM} h^2$ depends very sensitively on some input parameter(s): on m_t and $m_{1/2}$ in the focus point region; on the LSP–sfermion mass splitting in the co–annihilation regions; and on $2m_{\tilde{\chi}_1^0} - m_A$ in the Higgs pole region.

This objection to $\tilde{\chi}_1^0$ as DM triggered a fair amount of work in recent years on non–minimal scenarios, some of which I will briefly discuss in the next section. However, I first want to point out that the "bulk" region, where a bino–like $\tilde{\chi}_1^0$ has sufficiently large anni–hilation cross section due to the exchange of sufficiently light sfermions (mostly sleptons) without unduly strong dependence on input parameters, still exists if one takes the un–certainties discussed above seriously. An example is given in Table 3, which saturates the limits on m_t, m_h and $m_{\tilde{\tau}_1}$, but gets $\Omega_{\rm DM}$ "right on the money" with a sparticle spectrum in easy range of near–future experiments.

Table 2: Example for an allowed mSUGRA parameter space point in the "bulk" region. All mass parameters are in GeV. The first three rows give input parameters, the remaining quantities are calculated.

Quantity	Value	Quantity	Value
m_t	185	m_0	70.3
$\text{sign}(\mu)$	+1	$m_{1/2}$	181.3
$\tan\beta$	6	A_0	-375
$m_{\tilde{\chi}_1^0}$	67.9	$m_{\tilde{e}_R}$	108
$m_{\tilde{\chi}_2^0}$	127	$m_{\tilde{e}_L}$	152
$m_{\tilde{\chi}_3^0}$	332	$m_{\tilde{\nu}_e}$	130
$m_{\tilde{\chi}_4^0}$	351	$m_{\tilde{\tau}_1}$	99
$m_{\tilde{\chi}_1^\pm}$	126	$m_{\tilde{\tau}_2}$	155
$m_{\tilde{\chi}_1^\pm}$	351	$m_{\tilde{\nu}_\tau}$	129
m_h	111	m_A	355
m_H	356	$m_{H^\pm}$	128.4
$m_{\tilde{g}}$	452	$m_{\tilde{t}_1}$	240
$m_{\tilde{d}_R}$	410	$m_{\tilde{t}_2}$	470
$m_{\tilde{u}_R}$	411	$m_{\tilde{b}_1}$	377
$m_{\tilde{d}_L}$	431	$m_{\tilde{b}_2}$	412
$\Omega_{\tilde{\chi}_1^0} h^2$	0.114	$Br(b \to s\gamma)$	$2.7 \cdot 10^{-4}$

3. Nonminimal scenarios

We saw in Fig. 1 that in mSUGRA most of the $(m_0, m_{1/2})$ plane is excluded by the

DM constraint (2) if the other parameters are held fixed. The reason is that "generically", $\tilde{\chi}_1^0$ is bino–like in mSUGRA. This means that it mostly annihilates from a $P-$wave initial state (which increases the DM density by a factor ~ 7, relative to annihilation from an $S-$wave); only annihilates via $U(1)_Y$ interactions, which have the smallest gauge coupling of the three SM factor groups; and mostly annihilates through the exchange of sfermions in the $t-$ and $u-$channel, which are often significantly heavier than $\tilde{\chi}_1^0$. Evidently the annihilation cross section could be increased, and hence the relic density reduced, if some or all of these suppression factors could be removed, without having to change the cosmology.

In particular, $\tilde{\chi}_1^0$ can be made higgsino–like in a number of ways: by allowing the Higgs soft masses at the input (GUT) scale to exceed the sfermion masses [24]; by reducing the input scale from $M_X \simeq 2 \cdot 10^{16}$ GeV to some value around 10^{10} GeV [25]; or by reducing the gluino mass at the input scale relative to the electroweak gaugino masses [26]. Similarly, $\tilde{\chi}_1^0$ will be wino–like if the $SU(2)$ gaugino mass M_2 is smaller than the $U(1)_Y$ gaugino mass M_1 at the weak scale, which requires $M_2 < M_1/2$ at scale M_X [27]. Finally, the biggest (effective) DM annihilation cross section arises if $\tilde{\chi}_1^0$ is nearly degenerate with a strongly interacting sparticle, e.g. $\tilde{t}_1$, leading to strong co–annihilation [22]; this option even exists in mSUGRA. The trouble with all these modifications is that they do not really improve the situation. In particular, they do not increase the fraction of the (now enlarged) parameter space where the constraint (2) is satisfied; nor do they reduce the finetuning required to satisfy this constraint.

This is illustrated in Fig. 3, which shows $\Omega_{\tilde{\chi}_1^0} h^2$ as a function of one parameter. This parameter is A_0 (which controls $m_{\tilde{t}_1}$) for the (red) dot–dashed curve; the ratio of squared Higgs and sfermion soft masses for the dashed (blue) curve; and the ratio of $U(1)_Y$ and $SU(2)$ gaugino masses for the solid (dark green) curve. We see that in all cases the relic density depends very strongly on this parameter if it is in the desired range (2), which is indicated by the shaded (light green) band. In the first two cases the curve ends after dropping steeply, so the desired relic density is again obtained close to the edge of the allowed parameter space. In the last case the curve extends far beyond the point where $\Omega_{\tilde{\chi}_1^0} h^2$ is in the right range. In fact, in this part of the curve the relic density only depends relatively weakly on the plotted parameter. However, in order to have this rather flat part of the curve coincide with the desired range (2), one either needs a very heavy LSP, well in excess of 1 TeV, which would lead to severe finetuning in the Higgs sector; or one needs non–standard cosmology to raise the relic density for parameters that are phenomenologically acceptable.

This brings me to the issue of non–standard cosmology. In the minimal scenario one assumes that $\tilde{\chi}_1^0$ was in full thermal equilibrium in the early Universe, which requires [28]

$$n_{\tilde{\chi}_1^0} \langle v \sigma_{\mathrm{ann}}^{\mathrm{eff}} \rangle > H = \sqrt{\frac{\rho_{\mathrm{tot}}}{3 M_{\mathrm{Pl}}^2}} \,. \tag{6}$$

Here $n_{\tilde{\chi}_1^0}$ is the $\tilde{\chi}_1^0$ number density, $\sigma_{\mathrm{ann}}^{\mathrm{eff}}$ is the effective sparticle to particle annihilation cross section, which might include co–annihilation effects [29], v is the relative velocity of the two annihilating sparticles, $\langle \ldots \rangle$ denotes thermal averaging, H is the Hubble parameter, ρ_{tot} is the total energy density of the Universe, and $M_{\mathrm{Pl}} \simeq 2.4 \cdot 10^{18}$ GeV is
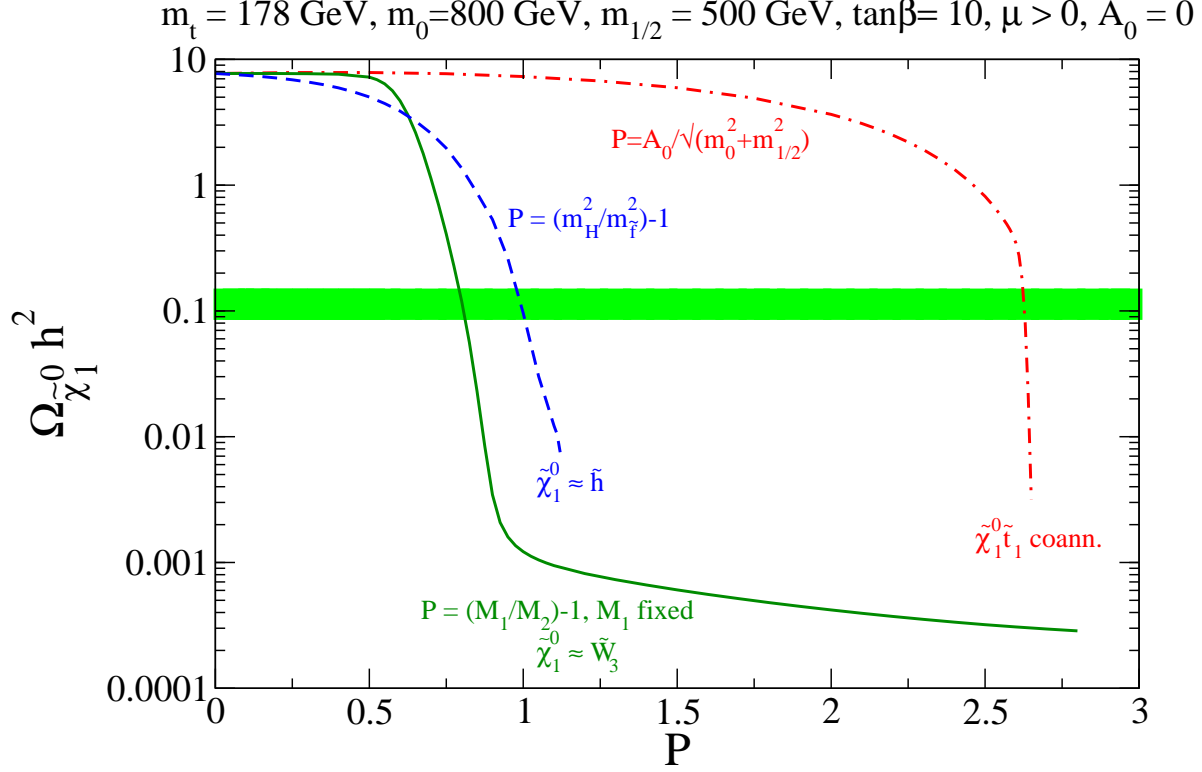
Figure 3: The $\tilde{\chi}_1^0$ relic density plotted as function of one parameter, which measures the deviation from the indicated mSUGRA starting point. The desired range (2) is indicated by the shaded (light green) band. See the text for further details.

the reduced Planck mass. Note that both sides of this relation depend strongly on the temperature T. For $T < m_{\tilde{\chi}_1^0}$ this dependence becomes exponential on the lhs, whereas in standard cosmology it's only a power–law on the rhs. Clearly the inequality can therefore not be satisfied at very low T. The relic density depends crucially at the "freeze–out" temperature T_f, where the inequality becomes an equality, with lower T_f corresponding to lower $\Omega_{\tilde{\chi}_1^0}$ since $n_{\tilde{\chi}_1^0} \propto \exp(-m_{\tilde{\chi}_1^0}/T)$. "Standard cosmology" means that the expression for H given in (6) holds, and that the Universe at $T \simeq T_f$ was radiation–dominated with only SM degrees of freedom as relativistic particles. This allows to compute the rhs in Eq.(6) as function of T, and yields $T_f \simeq m_{\tilde{\chi}_1^0}/20$. Clearly we can increase T_f, and hence $\Omega_{\tilde{\chi}_1^0}$, by increasing $H(T)$. Several ways to do so have been suggested [30], which could make a wino–like $\tilde{\chi}_1^0$ with reasonable mass a good DM candidate.

Of course, a bino–like $\tilde{\chi}_1^0$ typically has too *large* a relic density. Increasing $H(T)$ would make the situation even worse. In principle it should also be possible to cook up

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scenarios where $H(T)$ is reduced, but I am not aware of any studies along these lines. Another possibility is to dilute the $\tilde{\chi}_1^0$ density after freeze–out by releasing entropy from some late particle decay. The point is that one actually calculates the *ratio* of $n_{\tilde{\chi}_1^0}$ and the entropy density. In the standard calculation an absolute number for $\Omega_{\tilde{\chi}_1^0}$ is derived by assuming that the entropy density per comoving volume remained constant for $T < T_f$. If a late decay significantly increased the entropy density, it would reduce the $\tilde{\chi}_1^0$–to–entropy ratio, and hence $\Omega_{\tilde{\chi}_1^0}$. In order not to mess up Big Bang nucleosynthesis, this decay should happen at $T > 1$ MeV, but this still leaves several orders of magnitude in T, and twice as many orders of magnitude in lifetime of the decaying particle, where this mechanism could work. A good example for a late decaying particle is a hidden sector field, nowadays called moduli. However, if this decaying particle couples directly to $\tilde{\chi}_1^0$, these decays can *increase* $\Omega_{\tilde{\chi}_1^0}$ [31]; recall that this is desirable if $\tilde{\chi}_1^0$ is higgsino– or wino–like.

Finally, I should mention that there are viable SUSY DM candidates other than the lightest neutralino. Every SUSY model must contain a gravitino. There are at least three different sources of gravitinos in the early Universe: direct production from the thermal plasma; production from the decay of MSSM sparticles before the latter froze out; and decay of the lightest visible–sector sparticle at $T < T_f$. It is therefore not surprising that one can arrange things such that one gets the right relic density for pretty much any combination of visible–sector soft breaking parameters, e.g. by choosing appropriate values of the gravitino mass and of the reheat temperature after inflation. Since gravitino DM is treated in three contributions to these Proceedings [32], I will not discuss it any further, except for making the obvious remark that it is experimentally impossible to prove that gravitino DM indeed exists; its couplings to ordinary matter are just too weak.[‖] This is true also for another SUSY DM candidate, the axino [33].

4. Claimed WIMP detections

This brings me to the issue of WIMP detection. In fact, there are several particle physics observations that have been interpreted as positive evidence for particle DM.

The first is the DAMA observation of a statistically significant annual modulation in the observed event rate, interpreted as being due to the scattering of ambient DM particles off the nuclei in the detector [34]. More recent stringent limits from other direct WIMP searches [7] prove that the DAMA signal cannot be due to a SUSY WIMP. As far as I know, some (even) more exotic DM particles might still be compatible with all data [35], but I personally am very sceptical about this observation.

The other positive evidence all comes from the observation of fluxes of energetic particles in the vicinity of Earth. In particular, it has recently been pointed out [36] that an excess in photons with energy in the few GeV range can be explained by WIMP annihilation into $b\bar{b}$ pairs; this can even be described by mSUGRA, if one allows a "boost factor" in the annihilation rate, which could e.g. be due to small–scale clumpiness of the halo. This scenario also improves the description of the positron flux at a few tens of GeV,

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[‖]One *can* perhaps *dis*prove this possibility in certain cases, by studying gravitinos in the lab [32]. However, a failure to disprove does not make a proof.

and of the antiproton flux below 1 GeV. Moreover, the photon data are good enough to reconstruct the DM distribution in our galaxy; one finds structures (rings) at radii which coincides with structures in the visible galaxy (a gas ring and a ring of stars). This sounds quite impressive. However, I find it difficult to assess the significance of this observation. The crucial question is how reliable the "SM" predictions for the background fluxes are. Among other things, they rest on the assumption that the CR fluxes (of protons and electrons) are essentially the same everywhere in our galaxy. We know that the distribution of hot gas, of magnetic fields, of starburst regions etc is quite inhomogeneous; given that the excess in all cases is only a factor of a few, I would personally not want to bet money that the observed deviations are indeed due to WIMPs.

Finally, an excess of 511 keV photons from near (but not right at) the galactic center has been interpreted as light DM particles χ annihilating or decaying into e^-e^+ pairs [37]. If $m_\chi \leq 100$ MeV, the positrons would be slowed down sufficiently fast to annihilate (mostly) at rest; this bound has very recently been lowered to 20 MeV by considering emission of photons during the decay or annihilation [38]. χ could not be the lightest neutralino in an R–parity conserving MSSM (with non–universal gaugino masses, to allow such a light neutralino), since its annihilation cross section would be much too small. A decaying particle does not fit the angular distribution of the signal very well [39]. On the other hand, there might be some connection with extended, $N = 2$, SUSY [40]. However, astrophysical explanations of this observation have also been suggested [41].

5. Summary and conclusions

The lightest neutralino $\tilde{\chi}_1^0$ remains the best motivated DM candidate. It remains viable even in the simplest models of both particle physics (mSUGRA) and cosmology (standard cosmology up to temperatures of a few dozen GeV at least). Imposing the relic density constraint in this framework greatly reduces the size of the allowed parameter space, but does not reduce most lower bounds on sparticle and Higgs boson masses significantly. Scenarios with little finetuning in both the Higgs and DM sector are still allowed, if the top mass is near the upper end of its experimentally determined range and the lightest Higgs boson is close to the lower bound on its mass, as indicated by the (not very compelling) ALEPH hint of a Higgs discovery [42].

Non–universal SUGRA models do not increase the fraction of the (enlarged) parameter space that satisfies the relic density constraint, nor do they reduce the finetuning required to satisfy this constraint unless one also modifies cosmology (in the direction of enhancing the relic density). Other SUSY DM candidates exist. The gravitino is as well motivated from the particle physics side as the neutralino, but unlike the case of thermal WIMPs, nothing singles out the desired relic density even on a logarithmic scale.

Several distinct experimental observations have been interpreted as positive evidence for (mutually incompatible) WIMP Dark Matter, but only one them [36] can be interpreted as evidence for a neutralino WIMP without violating other constraints. This particular observation looks quite intriguing, but I wouldn't call it compelling.

This raises the question what kind of experimental evidence would be required to

make a compelling case for neutralino Dark Matter. I believe that observation of a WIMP signal by itself will not be sufficient. Astroparticle physics experiments cannot discover supersymmetry before the LHC does, contrary to claims one sometimes sees in the literature. To be sure, if they (and we) are lucky, a compelling WIMP signal might be found before he LHC commences operations, but it will be impossible to convince people that this WIMP is a superparticle; other candidates exist already now, and many more are sure to be invented as soon as a signal is established. Collider experiments will be necessary to establish that this WIMP is indeed a superparticle. Such experiments should eventually also be able to determine the masses and couplings one needs to know in order to compute the total LSP annihilation cross section [43], which will allow to calculate its relic density in a variety of cosmological models. The combination of these results from colliders with WIMP detection experiments will thus allow us to probe the Universe at a temperature some four or five orders of magnitude above that at the onset of nucleosynthesis, which currently is the earliest well established epoch. Collider physics and astroparticle physics should therefore not be seen as competitors, but as partners.

6. Acknowledgements

7. References

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